Article

The Early Effects of Nuss Surgery on Cardiopulmonary Function in Patients With Pectus Excavatum

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AIM: Pectus excavatum (PE) is a common congenital chest wall deformity that can impair cardiopulmonary function. While minimally invasive Nuss surgery is widely recognized for its cosmetic benefits, its early effects on cardiopulmonary performance are still unclear. This study aimed to investigate the changes in restrictive breathing patterns and cardiac parameters in the early postoperative period.
METHODS: A retrospective analysis was performed on 97 patients (26 females, 71 males) treated for pectus excavatum with a Haller index (HI) $\geq$3.25 at the Department of Thoracic Surgery between October 2008 and July 2020. Spirometric measurements were performed to assess lung function, including forced expiratory volume in one second (FEV1) and forced vital capacity (FVC). Cardiac parameters such as left ventricular ejection fraction (EF) and right ventricular diameter (RVD) were determined using transthoracic echocardiography. The examinations were performed preoperatively and six months postoperatively.
RESULTS: Significant improvements were observed in FVC (68.3% to 75.4%, $p = 0.01$) and EF (55.2% to 62.8%, $p = 0.02$) after the Nuss surgery, while the changes in FEV1 ($p = 0.07$) and RVD ($p = 0.09$) were not statistically significant. A subgroup analysis by HI severity showed that patients with moderate HI (3.25–4.0) had significantly higher preoperative ($p = 0.0001$) and postoperative ($p = 0.0007$) FVC, as well as preoperative ($p = 0.004$) and postoperative ($p = 0.002$) EF compared to those with severe HI (>4.0). Differences in ΔFVC ($p = 0.15$) and ΔEF ($p = 0.20$) between the groups were not statistically significant. Notably, FEV1 showed greater improvement in the moderate group ($p = 0.035$). An age-based analysis showed that patients under 18 years had significantly higher preoperative ($p = 0.003$) and postoperative ($p = 0.002$) FVC and postoperative EF ($p = 0.008$), though ΔFVC ($p = 0.33$) and ΔEF ($p = 0.25$) did not differ between age groups. Although FEV1 increased more in younger patients, this difference was not significant ($p = 0.06$). Gender-based analysis demonstrated that female patients had significantly higher preoperative ($p = 0.02$) and postoperative ($p = 0.05$) FVC, as well as postoperative EF ($p = 0.03$), compared to male patients. Although some parameters did not reach significance, the trends suggest potential long-term cardiopulmonary benefits.
CONCLUSIONS: Nuss surgery leads to a significant improvement in FVC and EF, especially in younger patients and those with moderate HI deformities. Although some changes were not statistically significant, the overall trends suggest potential long-term cardiopulmonary benefits. Further studies are needed to confirm these results and evaluate long-term outcomes.

Keywords: pectus excavatum; minimally invasive surgery; Nuss surgery cardiopulmonary function; echocardiography; pulmonary function tests

Introduction

As the most prevalent congenital chest wall deformity, pectus excavatum (PE) is characterized by an inward depression of the sternum toward the chest cavity, manifesting more frequently in males. Although the etiology is still unclear, PE is strongly associated with a genetic predisposition and connective tissue abnormalities. This is reflected in the frequent coexistence with conditions such as Marfan syndrome and Ehlers-Danlos syndrome, suggesting a link to abnormalities in connective tissue metabolism. About 40% of PE cases have a family history, and mutations in the FBN1 gene, which codes for fibrillin-1, have been associated with reduced mechanical strength of connective tissue. This weakening increases the flexibility of the chest wall and favors deformities. Pathologically, abnormal cartilage and rib growth can lead to an inward displacement of the sternum [1–4].

While mild cases of PE are often considered a cosmetic problem, severe cases can significantly affect respiratory and cardiac function by compressing the heart and lungs. Symptoms such as shortness of breath, fatigue, chest pain, and palpitations affect quality of life [5,6].

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In 1998, Dr. Donald Nuss introduced the minimally invasive Nuss procedure, which has since become the standard procedure for PE treatment. In this procedure, the deformity is corrected by inserting steel bars under the sternum and repositioning the chest wall anatomically. Compared to conventional open surgery, the Nuss procedure offers numerous advantages, including a shorter recovery time, less post-operative pain, and a better cosmetic result. Meta-analyzes report success rates of over 90% in improving respiratory and cardiac function as well as high patient satisfaction [7–9].

Pulmonary function tests (PFTs) are crucial for the objective assessment of lung capacity and airway function. In this study, forced expiratory volume in one second (FEV1) and forced vital capacity (FVC) were used as the main PFT parameters. FEV1 measures the volume of air exhaled in the first second of forced breathing, while FVC quantifies the total maximum exhaled air volume. Cardiac function was assessed using transthoracic echocardiography (TTE), a non-invasive imaging technique that provides a comprehensive overview of the structure and function of the heart [10,11].

Using retrospective analysis, this study aims to evaluate the early impact of Nuss surgery on respiratory capacity and cardiac performance in patients with PE. The dual role of Nuss surgery is emphasized in the study, which demonstrates the efficacy of the procedure in achieving both cosmetic and functional improvements. These findings are consistent with the current literature.

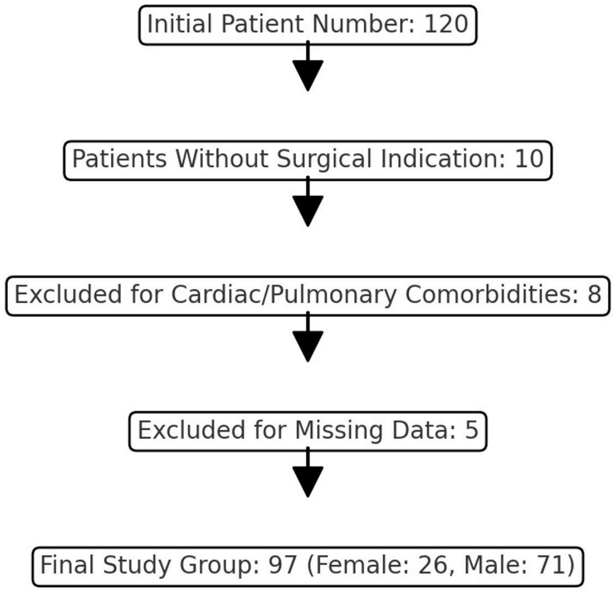

Fig. 1. Flowchart illustrating the inclusion and exclusion process for the study patients.

Materials and Methods

Study Design and Scope

This retrospective study included 97 patients diagnosed and treated for PE in the Department of Thoracic Surgery between October 2008 and July 2020. Patients with a Haller index (HI) $\geq$3.25 were included to investigate the early effects of Nuss surgery on respiratory and cardiac function.

Selection of Patients

Inclusion criteria were the presence of a surgical indication for PE, regular postoperative follow-up, and the availability of complete data sets. Patients with significant cardiac or pulmonary comorbidities, those for whom non-surgical treatment was recommended, and those with incomplete data were excluded. Of the original 120 patients, 23 were excluded due to lack of surgical indication (10 patients), comorbid conditions (8 patients), or incomplete/unverifiable data (5 patients). Thus, the final study population consisted of 97 patients (26 females, 71 males) (Fig. 1).

Data Collection and Analysis

Patient demographics, diagnostic methods, surgical procedures, and postoperative outcomes were retrospectively collected from hospital records. The HI was calculated from chest CT scans using standard methods. Spirometric parameters, including FEV1 and FVC, were measured preoperatively and six months postoperatively following American Thoracic Society (ATS) and European Respiratory Society (ERS) standards [12]. Cardiac function parameters such as left ventricular ejection fraction (EF) and right ventricular diameter (RVD) were determined using TTE. Standardized protocols and equipment were used for all examinations to ensure consistency and reliability.

Surgical Method

All patients underwent minimally invasive Nuss surgery by an experienced surgical team using video-assisted thoracoscopy. Steel bars were placed under the sternum to correct the deformity and were left in place for two to four years to ensure stabilization of the chest wall.

Postoperative Pain Treatment

The treatment protocol included the administration of epidural analgesics or intravenous opioids during the initial 48–72-hour period. This was followed by the administration of oral analgesics, such as paracetamol or non-steroidal anti-inflammatory drugs (NSAIDs). Patients also participated in guided breathing exercises and a tailored rehabilitation program to improve recovery and avoid complications.

In addition, individualized pain management protocols were developed based on the patients' specific needs. For example, patients with a low pain threshold or opioid tolerance were offered multimodal analgesia, which included infiltration with local anesthetics and supportive medication such as gabapentin. Pain intensity was monitored daily using a visual analog scale (VAS), and treatment was adjusted accordingly. Psychological support was offered to selected patients to alleviate their anxiety. Regular one-on-one meetings with healthcare providers ensured that patients adhered to their pain management plans. This individualized approach has both improved patient satisfaction and reduced pulmonary complications.

Postoperative Breathing Exercises

Within 24 hours of surgery, patients began breathing exercises, including incentive spirometry and diaphragmatic breathing. These exercises were performed three to five times daily during hospitalization under the supervision of a physiotherapist. On discharge, patients were given detailed instructions on how to continue these exercises at home. During outpatient visits to the clinic, adherence to the exercises was checked, and patients who adhered better to the exercises showed a significant improvement in postoperative lung function. This underscores the critical importance of breathing exercises in optimizing cardiopulmonary recovery.

Statistical Analysis

The normality of the data was tested using Kolmogorov-Smirnov and Shapiro-Wilk tests. Variables such as EF and FVC met the normality assumption, whereas FEV1 did not. Continuous variables were expressed as mean $\pm$ standard deviation (SD) if they followed a normal distribution or as median and interquartile range (IQR) if they were not normally distributed. Parametric tests (e.g., paired t-tests) were applied to normally distributed data, whereas non-parametric methods (e.g., Wilcoxon signed-rank test) were used for non-normally distributed data.

Subgroup analyses were performed to assess the effects of age, gender, and severity of the Haller index on the results. Patients were categorized into groups (<18 years (n = 58) or ≥18 years (n = 39), and by gender (female: n = 26; male: n = 71). Based on the HI, patients were classified as moderate (3.25–4.0; n = 54) or severe (>4.0; n = 43). Changes in FVC, EF, FEV1, and RVD were analyzed preoperatively and six months postoperatively using appropriate statistical methods. Non-parametric subgroup data were analyzed using the Mann-Whitney U test, with effect sizes determined by r and Cliff's delta.

The sample size was calculated to ensure sufficient statistical power (80%) with a significance level of $\alpha = 0.05$. A minimum number of 90 patients was set to detect significant differences, which was achieved with the inclusion of 97 patients. All statistical analyses were performed using IBM SPSS Statistics v26 (IBM SPSS Statistics, Chicago, IL, USA), with results considered significant at a significance level of $p < 0.05$ and reported with 95% confidence interval (CI).

Table 1. Distribution of postoperative complications.

Type of complication	n	%
Minor wound infection	4	4.1
Pneumothorax	2	2.1
Pleural effusion	2	2.1
Bar displacement	2	2.1
Other (e.g., temporary skin numbness)	1	1.0
Total	11	11.3

n, number of patients.

Results

Demographic and Operational Data

The age of the patients ranged from 12 to 42 years, with a mean age of 21.4 $\pm$ 6.5 years. Of the 97 patients included, 26.8% were female (n = 26) and 73.2% were male (n = 71). The mean duration of surgery was 45 $\pm$ 10.5 minutes (range: 25–65 minutes), and the mean postoperative hospital stay was 4 $\pm$ 0.8 days (range: 3–5 days).

The overall rate of postoperative complications was 11.3%, including bar displacement (2.1%), pneumothorax (2.1%), minor wound infection (4.1%), pleural effusion (2.1%) and other minor complications (1.0%) (Table 1). No significant late complications were observed at one week, one month, three months, and six months postoperatively. None of the patients required intensive medical care, and the postoperative course was unremarkable in all cases.

General Results

Significant improvements in respiratory and cardiac function were observed after the Nuss operation. FVC increased from 68.3% (95% CI: 67.27–69.33) preoperatively to 75.4% (95% CI: 74.42–76.38) postoperatively, reflecting an improvement of +10.4% (p = 0.01). Similarly, left ventricular EF improved from 55.2% (95% CI: 54.34–56.06) to 62.8% (95% CI: 62.04–63.56) postoperatively, representing a +13.8% increase (p = 0.02). Although FEV1 showed a postoperative increase from 74.5% [72.1–77.2] to 77.3% [74.8–79.5], the change (+3.8%) did not reach statistical significance (p = 0.07). Likewise, RVD decreased from 36.1 mm [35.2–37.5] to 34.5 mm [33.1–35.8], representing a –4.4% reduction, though this change was also not statistically significant (p = 0.09) (Table 2).

The postoperative improvements in FVC and EF are shown in Fig. 2 and demonstrate a significant improvement in these parameters. Although the changes in FEV1 and RVD were not statistically significant, the positive trends observed in these parameters are seen as evidence of the overall effectiveness of the surgical intervention. The error bars in the figure represent standard deviations.

Subgroup Analyzes

Gender Differences

In Table 3, a comparison between male and female groups shows differences in functional improvements. The female

Table 2. Comparison of preoperative and postoperative values.

Parameter	Preoperative (median [IQR] or mean ± SD, 95% CI)	Postoperative (median [IQR] or mean ± SD, 95% CI)	Change (%)	*p*	*t*/Z
FVC (%)	68.3 ± 5.2 (67.27–69.33)	75.4 ± 4.9 (74.42–76.38)	+10.4	0.01*	*t* = 3.45
FEV1 (%)	74.5 [72.1–77.2]	77.3 [74.8–79.5]	+3.8	0.07†	Z = –1.89
EF (% left ventricle)	55.2 ± 4.3 (54.34–56.06)	62.8 ± 3.8 (62.04–63.56)	+13.8	0.02*	*t* = 4.12
RVD (mm)	36.1 [35.2–37.5]	34.5 [33.1–35.8]	–4.4	0.09†	Z = –1.67

Parametric data (FVC, EF) are presented as mean ± standard deviation (mean ± SD) and 95% confidence interval (CI), while non-parametric data (FEV1, RVD) are presented as median [interquartile range, IQR]. Paired *t*-tests were used for normally distributed variables, and Wilcoxon signed-rank tests for non-normally distributed variables. For parameters that met the normality assumption (FVC, EF), a dependent *t*-test was performed, while for parameters that did not meet the normality assumption (FEV1, RVD), the †Wilcoxon signed-rank test was used. *Statistical significance was set at $p < 0.05$.

IQR, interquartile range; SD, standard deviation; FVC, forced vital capacity; FEV1, forced expiratory volume in one second; EF, ejection fraction; RVD, right ventricular diameter.

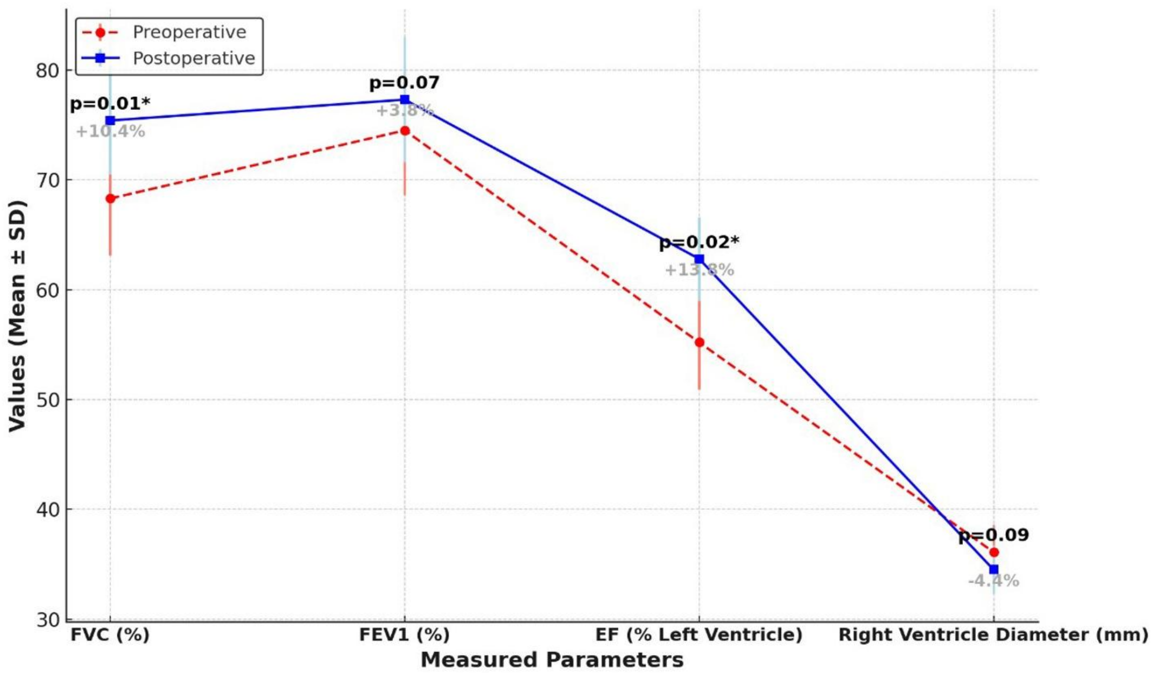

Fig. 2. Changes in cardiopulmonary function after Nuss surgery: pre- and postoperative FVC (%), FEV1 (%), EF (%) and RVD values (mm). *$p < 0.05$.

group had a higher FVC (76.5 ± 4.7%) than the male group (74.5 ± 4.9%) after the intervention, which is a statistically significant improvement in both cases (p = 0.05). EF also increased in both groups, in females from 56.2% [54.8–57.5] to 63.4 ± 3.9% (p = 0.03), in males from 54.4% [52.9–55.8] to 61.7 ± 4.1% (p = 0.05). The FEV1 value after the intervention was also slightly higher in females at 78.8% [76.5–80.2] than in males at 76.5% [74.9–78.0] (p = 0.05). RVD showed a similar trend, decreasing in both groups, from 36.0 mm [35.3–36.9] to 34.2 mm [33.5–35.3] in females and from 36.3 mm [35.5–37.2] to 34.7 mm [33.9–35.5] in males (p = 0.07). These results indicate that although both groups experienced statistically significant improvements, the extent of change differed between males and females.

Fig. 3 illustrates the gender-specific differences in the pre- and postoperative values of FVC and EF. The dark blue bar chart represents the increase in FVC (%), while the pink dashed line chart shows the improvement in EF (%), with the change being more pronounced in females. In addition, a light pink shaded area highlights the EF variations between different groups. As FVC and EF are measured on different scales, an approach with two vertical axes (FVC on the left y-axis and EF on the right y-axis) was chosen to represent both parameters accurately. There is only one horizontal axis that categorizes the preoperative and postoperative values by gender.

Table 3. Comparison between female and male groups.

Parameter	Female (median [IQR] or mean ± SD, 95% CI)	Male (median [IQR] or mean ± SD, 95% CI)	p	t-value/Z-value
FVC (%) pre	70.3 ± 5.2 (68.3, 72.3)	67.8 ± 5.4 (66.54, 69.06)	0.02*	t = 2.34
FVC (%) post	76.5 ± 4.7 (74.69, 78.31)	74.5 ± 4.9 (73.36, 75.64)	0.05*	t = 2.02
FEV1 (%) pre	75.0 [73.1–76.9]	73.5 [72.0–75.1]	0.08	Z = –1.45
FEV1 (%) post	78.8 [76.5–80.2]	76.5 [74.9–78.0]	0.05	Z = –1.95
EF (%) pre	56.2 [54.8–57.5]	54.4 [52.9–55.8]	0.07†	Z = –1.45
EF (%) post	63.4 ± 3.9 (61.9, 64.9)	61.7 ± 4.1 (60.75, 62.65)	0.03*	t = 2.16
RVD (mm) pre	36.0 [35.3–36.9]	36.3 [35.5–37.2]	0.09	Z = –1.55
RVD (mm) post	34.2 [33.5–35.3]	34.7 [33.9–35.5]	0.07	Z = –1.60

*The independent t-test was used for parameters that fulfill the normality assumption (e.g., FVC, EF). †The Mann-Whitney U test was used for parameters that do not meet the normality assumption (e.g., FEV1, RVD, and preoperative EF). Parametric data are expressed as mean ± standard deviation (mean ± SD) and 95% CI. Non-parametric data are expressed as median [interquartile range, IQR]. Statistical significance threshold: $p < 0.05$. pre, preoperative; post, postoperative.

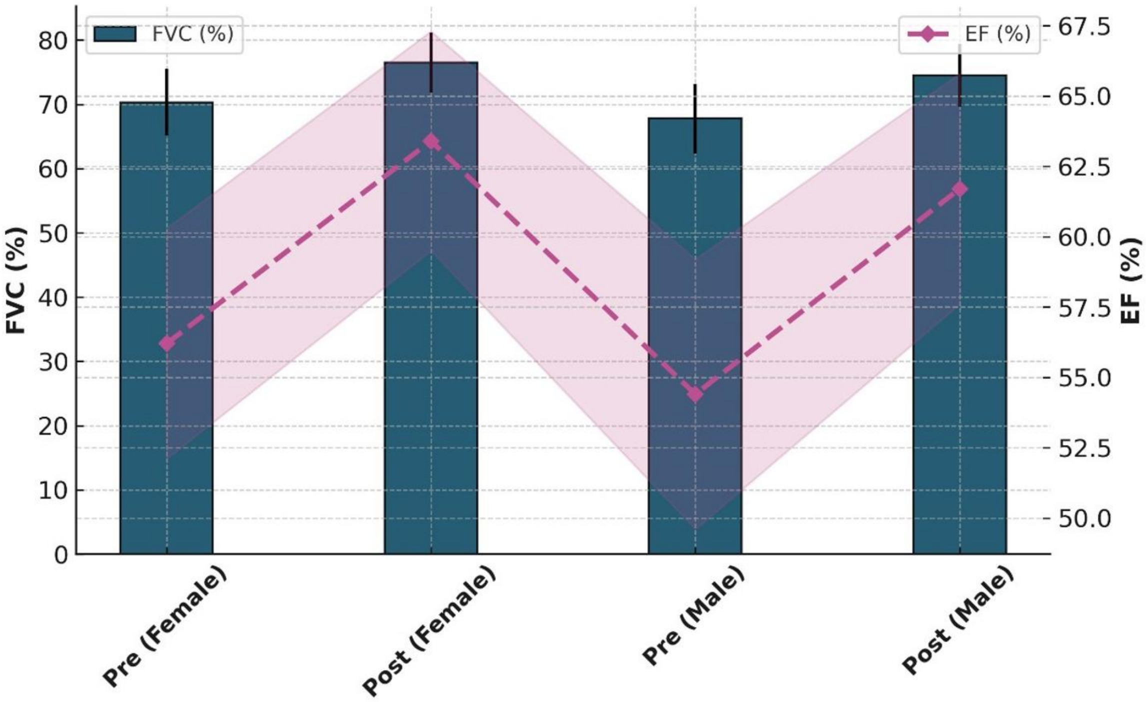

Fig. 3. Changes in preoperative and postoperative FVC and EF. Pre, preoperative; Post, postoperative.

Age-Related Differences

Patients under 18 years of age showed greater improvements in FVC and EF compared to older patients. FVC increased from 70.5 ± 5.0% to 77.2 ± 4.6% in the younger group, while it improved from 67.3 ± 5.2% to 74.0 ± 4.8% in the older group (p = 0.003 preoperatively, p = 0.002 postoperatively). Similarly, EF increased from 56.2 ± 4.1% to 64.0 ± 3.8% in the younger patients and from 54.5 ± 4.7% to 61.8 ± 4.0% in the older patients (p = 0.008 postoperatively). However, ΔFVC (p = 0.33) and ΔEF (p = 0.25) showed no statistically significant differences between the two groups. The FEV1 values also did not differ significantly between the groups either preoperatively (p = 0.17) or postoperatively (p = 0.06). Although RVD decreased postoperatively in both groups, this change was not statistically significant (p = 0.34) (Table 4).

Severity of the HI

Postoperative improvements in FVC, EF, and FEV1 were observed in both groups; however, the differences between the moderate and severe HI groups were different. Patients with moderate HI had significantly higher preoperative and postoperative FVC and EF values than patients with severe HI. Although ΔFVC and ΔEF showed numerical differences (6.5 ± 2.0% vs. 5.9 ± 2.1%, p = 0.15 and 7.0 ± 2.3% vs. 6.4 ± 2.2%, p = 0.20, respectively),

Table 4. Age-dependent comparison of cardiopulmonary outcomes after Nuss surgery.

Parameter	Under 18 years (n = 58)	18 years and above (n = 39)	p	t/Z	Cohen's d
FVC (%) pre	70.5 ± 5.0	67.3 ± 5.2	0.003*	t = 3.02	0.63
FVC (%) post	77.2 ± 4.6	74.0 ± 4.8	0.002*	t = 3.27	0.68
ΔFVC (%)	6.7 ± 2.1	6.3 ± 1.9	0.33	t = 0.98	0.20
EF (%) pre	56.2 ± 4.1	54.5 ± 4.7	0.06	t = 1.85	0.38
EF (%) post	64.0 ± 3.8	61.8 ± 4.0	0.008*	t = 2.72	0.56
ΔEF (%)	7.8 ± 2.2	7.3 ± 2.0	0.25	t = 1.16	0.24
FEV1 (%) pre	75.0 [72.8–76.9]	74.2 [72.0–75.8]	0.17	Z = –1.37	-
FEV1 (%) post	78.8 [76.9–80.5]	76.5 [74.7–78.2]	0.06	Z = –1.88	-
RVD (mm) pre	36.0 [35.3–37.0]	36.3 [35.6–37.5]	0.44	Z = –0.78	-
RVD (mm) post	34.2 [33.4–35.5]	34.7 [33.8–35.9]	0.34	Z = –0.96	-

Parametric data (FVC, EF) are expressed as mean ± standard deviation (SD), and non-parametric data (FEV1, RVD) are expressed as median [interquartile range, IQR]. Δ (delta) values represent the difference between postoperative and preoperative measurements.

For normally distributed data, a dependent t-test was used for within-group comparisons and an independent t-test for between-group comparisons. For non-normally distributed data, the Mann-Whitney U test was used.

Cohen's d was calculated to measure the effect size (small: 0.2, medium: 0.5, large: 0.8).

Statistically significant differences were evaluated at $p < 0.05$ (*). Non-significant results ($p > 0.05$) indicate that the observed changes did not reach statistical significance, although trends were identified.

these did not reach statistical significance. In contrast, ΔFEV1 was significantly higher in the moderate HI group (3.4% [2.8–4.0] vs. 2.5% [2.1–3.2], $p = 0.035$), indicating a more pronounced postoperative improvement in lung function. RVD decreased postoperatively in both groups, but the change was not statistically significant ($p = 0.27$). These results suggest that although both groups benefited from Nuss surgery, patients with moderate HI exhibited a greater improvement in lung function, probably due to better thoracic compliance and cardiopulmonary adaptation (Table 5).

Discussion

This study shows that Nuss surgery significantly improves both respiratory and cardiac function, as evidenced by the increase in FVC (from 68.3% to 75.4%) and EF (from 55.2% to 62.8%) [13]. These results emphasize the physiological benefits of anatomical correction, including improved lung expansion and reduced mechanical pressure on the heart, which in turn alleviates cardiac workload. Effective postoperative pain management, including epidural analgesia and intravenous opioids in the first 72 hours, played a critical role in facilitating early breathing exercises and maintaining pulmonary ventilatory capacity [14,15]. This individualized approach not only improved patient satisfaction but also minimized pulmonary complications, highlighting the importance of multimodal pain management strategies [16]. Future research should investigate alternative pain management protocols to assess their long-term impact on recovery and functional outcomes.

Postoperative breathing exercises play a key role in optimizing respiratory function and avoiding complications such as atelectasis. However, differences in patient compliance may have influenced lung function outcomes. Future research should focus on the development of standardized compliance monitoring tools and personalized exercise programs to better assess their long-term effects.

The results of this study confirm the functional cardiopulmonary benefits of Nuss surgery, particularly the significant improvements in FVC and EF, while also indicating a positive trend in FEV1 and RVD. These results are consistent with previous study by Jaroszewski *et al*. [17], which showed that the procedure reduces mechanical pressure on the heart and lungs, leading to improved physiological function.

Although the observed improvements in FEV1 and RVD were not statistically significant, the overall trend suggests that surgical correction may facilitate gradual cardiopulmonary adaptation over time. Previous study have shown that early postoperative pulmonary function tests may underestimate the full benefit of surgery, as lung compliance and respiratory muscle function continue to improve after the 6-month follow-up period [18]. This is consistent with the findings of Aronson *et al*. [18], who reported that FEV1 and FVC tend to stabilize and continue to improve at longer follow-up, highlighting the need for long-term monitoring. From a cardiovascular perspective, the reduction in RVD indicates potential relief of right ventricular compression, although it did not reach statistical significance. However, given that even small reductions in ventricular size have been associated with improved hemodynamic efficiency and reduced cardiac workload [19–21], these changes may be clinically relevant. Future studies that include longitudinal studies and advanced imaging techniques such as cardiac MRI may provide deeper insights into the long-term effects of Nuss surgery on cardiac function.

Table 5. Changes in cardiopulmonary parameters depending on the severity of the Haller index after the Nuss operation.

Parameter	HI moderate (n = 54)	HI severe (n = 43)	p	t/Z	Cohen's d
FVC (%) pre	71.2 ± 4.8	67.1 ± 5.1	0.0001*	$t = 4.03$	0.83
FVC (%) post	76.9 ± 4.6	73.5 ± 4.9	0.0007*	$t = 3.49$	0.72
ΔFVC (%)	6.5 ± 2.0	5.9 ± 2.1	0.15	$t = 1.43$	0.29
EF (%) pre	56.8 ± 4.2	54.2 ± 4.5	0.004*	$t = 2.92$	0.60
EF (%) post	63.8 ± 3.9	61.2 ± 4.1	0.002*	$t = 3.17$	0.65
ΔEF (%)	7.0 ± 2.3	6.4 ± 2.2	0.20	$t = 1.30$	0.27
FEV1 (%) pre	74.9 [72.5–76.8]	73.0 [71.4–74.6]	0.11	Z = −1.58	-
FEV1 (%) post	78.3 [76.2–79.7]	76.1 [74.3–77.8]	0.06	Z = −1.85	-
ΔFEV1 (%)	3.4 [2.8–4.0]	2.5 [2.1–3.2]	0.035*	Z = −2.10	-
RVD (mm) pre	36.4 [35.6–37.1]	36.1 [35.4–36.9]	0.19	Z = −1.30	-
RVD (mm) post	34.1 [33.3–35.0]	34.6 [33.8–35.4]	0.27	Z = −1.10	-

Parametric data (FVC, EF) are expressed as mean ± standard deviation (SD), while non-parametric data (FEV1, RVD) are expressed as median [interquartile range, IQR].

Δ (delta) values represent the difference between postoperative and preoperative measurements.

Moderate: Haller index (HI) 3.25–4.0; severe: HI >4.0.

For normally distributed data, a dependent t-test was used for within-group comparisons and an independent t-test for between-group comparisons. For non-normally distributed data, the Mann-Whitney U test was used.

Cohen's d was calculated to measure the effect size (small: 0.2, medium: 0.5, large: 0.8).

Statistical significance was set at $p < 0.05$ (*). Non-significant results ($p > 0.05$), which means that the observed changes did not reach statistical significance, although trends were observed.

No statistically significant changes in FEV1 or RVD were found between subgroups by gender, age, or Haller index ($p > 0.05$).

Although the changes in FEV1 and RVD were not statistically significant, their positive trend suggests a possible role in reducing cardiopulmonary stress. Even a modest reduction in right RVD may reduce cardiac compression, which could lead to an improvement in hemodynamic efficiency and overall quality of life over time. Similarly, the slight increase in FEV1 suggests possible progressive respiratory adaptation, particularly if pulmonary compliance and muscle function continue to improve postoperatively. To better understand the clinical relevance of these trends, future research should focus on longer follow-up periods and larger patient cohorts to determine whether these early postoperative improvements result in sustained functional benefits.

A subgroup analysis revealed that female patients had higher pre- and postoperative FVC and EF values compared to male patients. Rather than experiencing greater post-operative improvement, female patients maintained their pre-existing advantage in lung and heart function after surgery. This pattern may be influenced by intrinsic anatomic and physiologic factors, such as greater chest wall compliance and possible hormonal influences. These findings are consistent with previous study by Liu *et al*. [6], who reported better postoperative respiratory outcomes in female patients. However, given the unbalanced sex distribution in many pectus excavatum studies, including this study, further research with larger, sex-balanced cohorts is essential to determine whether these differences are genuinely sex-specific or driven by other confounding variables, such as baseline cardiopulmonary function and preoperative conditioning.

Age was another key factor for the postoperative outcome. Patients younger than 18 years showed a greater increase in FVC and EF, which may be due to greater chest wall flexibility and improved cardiopulmonary adaptability. This is consistent with the findings of Liu and Wen [22] and Wang *et al*. [10], who reported that younger patients tend to experience more favorable functional improvements after Nuss surgery. These benefits may be attributed to a more compliant thoracic structure and greater physiologic adaptability, which may allow for more efficient postoperative recovery. While these results highlight the potential benefits of early surgical intervention, larger prospective studies are needed to validate the long-term effects of age on surgical outcomes. Future studies should also consider the role of concomitant diseases such as connective tissue disorders (e.g., Marfan syndrome), which may affect both preoperative cardiopulmonary function and postoperative recovery. In addition, long-term follow-up studies focusing on complications such as bar displacement, chronic pain, and recurrence of deformities are crucial to assess the durability of the benefits of the procedure. The development of tailored rehabilitation protocols for elderly patients or those with severe deformities could further optimize postoperative recovery and address potential issues related to reduced chest wall compliance and slower physiological adaptation.

Patients with moderate HI showed greater postoperative improvements in FVC and EF compared to those with severe HI, suggesting that the extent of chest wall deformity may influence the degree of functional improvement. As noted by Gao *et al*. [4], severe deformities may impose biomechanical constraints that may limit the cardiopulmonary benefits of surgical correction. However, despite these challenges, clinically meaningful improvements were also observed in patients with severe HI, highlighting the efficacy of Nuss surgery in a wide range of deformity grades.

These results underscore the need for individualized postoperative treatment strategies, especially for patients with severe HI who may require additional rehabilitation interventions to maximize functional recovery. Tailored rehabilitation protocols, especially for older patients or those with reduced thoracic structures, could help overcome biomechanical limitations and enhance postoperative adaptation. Future research should focus on optimizing rehabilitation techniques and identifying key predictors of long-term functional improvement in patients with varying degrees of HI severity.

The overall complication rate in this study was 11.3%, in line with the 10–15% range reported in the literature [23,24], which underlines the safety and reliability of the Nuss procedure. Most complications, such as minor wound infections (4.1%) and rod dislocations (2.1%), were effectively managed via conservative treatment minimizing the need for additional surgical interventions. These favorable results highlight the importance of multidisciplinary postoperative care, including structured physiotherapy programs, which have been shown to promote recovery and reduce complication rates [25].

While the early benefits of Nuss surgery are well documented, its long-term effects, particularly the durability of cardiopulmonary improvements, require further investigation. A 10-year follow-up study by Jaroszewski *et al*. [17] demonstrated sustained improvements in cardiac function, suggesting that the benefits of the procedure extend well beyond the immediate postoperative period. However, these results may vary depending on factors such as patient age and severity of deformity, emphasizing the need for long-term, large-scale studies with different patient populations. Future research should also investigate the potential for late complications such as bar displacement or residual stiffness of the chest wall and evaluate how patient-specific factors influence long-term surgical success.

Limitations of the Study

The main limitations of this study are the retrospective design and the short follow-up period, which focused on early postoperative effects rather than long-term outcomes. Although strict inclusion and exclusion criteria were applied to minimize selection bias and ensure a homogeneous study population and standardized instruments such as spirometry and transthoracic echocardiography were used to reduce information bias, the inherent limitations of a retrospective study remain. Future prospective studies with longer follow-up periods are needed to validate these results and provide more robust conclusions.

Suggestions for Future Research

Prospective studies with longer follow-ups are needed to evaluate the long-term results of the Nuss procedure, especially its effects on different age groups. Future studies should focus on changes in cardiopulmonary parameters such as FVC and EF over time, as well as age-related effects on FEV1 and RVD. Regular follow-up at 6, 12, and 24 months should include pulmonary function tests, echocardiography, and, if necessary, cardiac magnetic resonance imaging (MRI). Future studies should also investigate the long-term effects of Nuss surgery in patients with severe HI (>4.0), focusing on the particular challenges of cardiopulmonary recovery and the higher risk of complications. Quality of life assessments using validated instruments such as the Short Form-36 Health Survey (SF-36) can also provide valuable insight into the long-term benefits of the procedure. Future studies should investigate the role of rehabilitation protocols tailored to individual patient profiles, including age, gender, and baseline cardiopulmonary function. Accordingly, subgroups that benefit most from specific postoperative strategies could be identified. These measures help identify late complications and contribute to the optimization of surgical outcomes and postoperative care.

Conclusions

This study emphasizes the positive effects of Nuss surgery on cardiopulmonary function, especially on the improvement of FVC and EF. The results suggest that younger patients and patients with moderate HI deformities may experience greater improvements, emphasizing the potential benefits of early surgical intervention. Although postoperative changes were observed in several cardiopulmonary parameters, further investigation is needed to determine the long-term effects of these improvements. Future studies should focus on refining patient selection criteria and evaluating the role of factors such as age, gender, and preoperative cardiopulmonary status on surgical outcomes. In conclusion, Nuss surgery is a valuable intervention for improving cardiopulmonary function in appropriate patients. However, larger studies and long-term follow-up are essential to validate these results and optimize treatment strategies.

Availability of Data and Materials

The data supporting the results of this study are available upon reasonable request to the corresponding author.

Author Contributions

TD conceived the study, drafted the manuscript, supervised the process, and made final revisions. TD, GC, and CD contributed to data collection and assisted in analyzing and interpreting the data. All authors have been involved in revising it critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

The study was approved by the Ethics Committee at Istanbul Training and Research Hospital (ethics approval number: June 26, 2020/450). Informed consent was obtained from all patients who participated in the study. The study was conducted in accordance with the principles of the Declaration of Helsinki.

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Conflict of Interest

The authors declare no conflict of interest.

References

[1] Tikka T, Webb J, Agostini P, Kerr A, Mannion G, Steyn RS, *et al*. Pectus patient information website has improved access to care and patient reported outcomes. Journal of Cardiothoracic Surgery. 2016; 11: 69. https://doi.org/10.1186/s13019-016-0470-7.

[2] Brungardt JG, Chizek PW, Schropp KP. Adult pectus excavatum repair: national outcomes of the Nuss and Ravitch procedures. Journal of Thoracic Disease. 2021; 13: 1396–1402. https://doi.org/10.21037/jtd-20-2422.

[3] Farina JM, Yinadsawaphan T, Jaroszewski DE, Aly MR, Botros M, Cheema KP, *et al*. The electrocardiographic manifestations of pectus excavatum before and after surgical correction. Journal of Electrocardiology. 2024; 82: 19–26. https://doi.org/10.1016/j.jelectrocard.2023.11.007.

[4] Gao Z, Huang S, Tang Y, Wang S, Zhuang W, Ding Y, *et al*. Factors influencing negative surgical outcomes in adult pectus excavatum patients undergoing Nuss procedure. Annals of Translational Medicine. 2021; 9: 1335. https://doi.org/10.21037/atm-21-3822.

[5] Janssen N, Coorens NA, Franssen AJPM, Daemen JHT, Michels IL, Hulsewé KWE, *et al*. Pectus excavatum and carinatum: a narrative review of epidemiology, etiopathogenesis, clinical features, and classification. Journal of Thoracic Disease. 2024; 16: 1687–1701. https://doi.org/10.21037/jtd-23-957.

[6] Brussels AR, Kim MS. Perioperative considerations in anesthesia for minimally invasive repair of pectus excavatum, Nuss procedure. Seminars in Pediatric Surgery. 2024; 33: 151459. https://doi.org/10.1016/j.sempedsurg.2024.151459.

[7] Casatori L, Pellegrino A, Messineo A, Ghionzoli M, Facchini F, Modesti A, *et al*. Differential influence of physical activity on cardiopulmonary performance and stroke volume assessed at cardiopulmonary exercise test in pectus excavatum: a pilot study. Frontiers in Physiology. 2022; 13: 831504. https://doi.org/10.3389/fphys.2022.831504.

[8] Yue F, Yang F, Chen Z, Zhao L, Jia Z. Effects of NUSS surgery on degree of flat thoracic cage, cardiopulmonary function, and bone metabolism in pectus excavatum patients of different ages. Updates in Surgery. 2024. https://doi.org/10.1007/s13304-024-02030-y. (online ahead of print)

[9] Ravasin A, Viggiano D, Tombelli S, Checchi L, Stefàno P, Voltolini L, *et al*. Heart Disease and Pectus Excavatum: An Underestimated Issue-Single Center Experience and Literature Review. Life. 2024; 14: 1643. https://doi.org/10.3390/life14121643.

[10] Wang L, Bi R, Xie X, Xiao H, Hu F, Jiang L. A modified Nuss procedure for recurrent pectus excavatum of adults. Frontiers in Surgery. 2022; 8: 814837. https://doi.org/10.3389/fsurg.2021.814837.

[11] Zhao S, Xue X, Li K, Miao F. Pectus excavatum, kyphoscoliosis associated with thoracolumbar spinal stenosis: a rare case report and literature review. BMC Surgery. 2022; 22: 266. https://doi.org/10.1186/s12893-022-01716-7.

[12] American Thoracic Society, European Respiratory Society. Standardization of Spirometry 2019 Update. An Official American Thoracic Society and European Respiratory Society Technical Statement. American Journal of Respiratory and Critical Care Medicine. 2019; 200: e70–e88. https://doi.org/10.1164/rccm.201908-1590ST.

[13] Park WJ, Son JW, Park KH, Kim YM, Nam JH, Choi KU, *et al*. Late complication of the Nuss procedure: recurrent cardiac tamponade. Yeungnam University Journal of Medicine. 2019; 36: 260–264. https://doi.org/10.12701/yujm.2019.00241.

[14] Udholm S, Maagaard M, Pilegaard H, Hjortdal V. Cardiac function in adults following minimally invasive repair of pectus excavatum. Interactive Cardiovascular and Thoracic Surgery. 2016; 22: 525–529. https://doi.org/10.1093/icvts/ivw007.

[15] Eldredge RS, Sabati A, Ochoa B, Viswanath V, Khoury E, Rassam K, *et al*. Cardiopulmonary impact of the minimally invasive repair of pectus excavatum in pediatric patients: a prospective pilot study. Journal of Pediatric Surgery. 2025; 60: 162177. https://doi.org/10.1016/j.jpedsurg.2025.162177.

[16] Barua A, Rao VP, Barua B, Majewski A. Patient satisfaction following minimally invasive repair of pectus excavatum: single surgeon experience. Journal of Surgical Technique and Case Report. 2012; 4: 86–88. https://doi.org/10.4103/2006-8808.110253.

[17] Jaroszewski DE, Farina JM, Gotway MB, Stearns JD, Peterson MA, Pulivarthi VSKK, *et al*. Cardiopulmonary Outcomes After the Nuss Procedure in Pectus Excavatum. Journal of the American Heart Association. 2022; 11: e022149. https://doi.org/10.1161/JAHA.121.022149.

[18] Aronson DC, Bosgraaf RP, Merz EM, van Steenwijk RP, van Aalderen WMC, van Baren R. Lung function after the minimal invasive pectus excavatum repair (Nuss procedure). World Journal of Surgery. 2007; 31: 1518–1522. https://doi.org/10.1007/s00268-007-9081-8.

[19] Nuss D, Obermeyer RJ, Kelly RE. Nuss bar procedure: past, present and future. Annals of Cardiothoracic Surgery. 2016; 5: 422–433. https://doi.org/10.21037/acs.2016.08.05.

[20] Garzi A, Prestipino M, Rubino MS, Di Crescenzo RM, Calabrò E. Complications of the "Nuss Procedure" In Pectus Excavatum. Translational Medicine @ UniSa. 2020; 22: 24–27.

[21] Song J, Wang Q, Pan Z, Wu C, Li Y, Wang G, *et al*. The safety and efficacy of the modified single incision non-thoracoscopic Nuss procedure for children with pectus excavatum. Frontiers in Pediatrics. 2022; 10: 831617. https://doi.org/10.3389/fped.2022.831617.

[22] Liu C, Wen Y. Research progress in the effects of pectus excavatum on cardiac functions. World Journal of Pediatric Surgery. 2020; 3: e000142. https://doi.org/10.1136/wjps-2020-000142.

[23] Ganescu O, LaRusso K, St-Louis E, Saint-Martin C, Cavalle-Garrido T, Zielinski D, *et al*. The utility of echocardiography and pulmonary

function testing in the preoperative evaluation of pectus excavatum. Journal of Pediatric Surgery. 2022; 57: 1561–1566. https://doi.org/10.1016/j.jpedsurg.2021.12.010.

[24] Dada RS, Hayanga JW, Abbas Khan MA, Toker A, Hayanga HK. A 36-Year-Old Female With Congenital Contractural Arachnodactyly and Pectus Excavatum Requiring Fourth-Time Redo Surgical Correction. Cureus. 2021; 13: e16701. https://doi.org/10.7759/cureus.16701.

[25] Akhtar M, Razick DI, Saeed A, Baig O, Kamran R, Ansari U, *et al*. Complications and Outcomes of the Nuss Procedure in Adult Patients: A Systematic Review. Cureus. 2023; 15: e35204. https://doi.org/10.7759/cureus.35204.